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Petrophysical analyses of hydrocarbon reservoirs and overpressure zones in Tertiary deep-marine strata in the northern Beaufort-Mackenzie Basin, Arctic Canada

K. Hu, J.R. Dietrich, Z. Chen, and P.K. Hannigan

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ABSTRACT

This report describes the petrophysical analyses of reservoir characteristics, hydrocarbon occurrences, and overpressure zones in deep-marine Tertiary strata in eight wells (Kenalooak J-94, Koakoak O-22, Kopanoar M-13, Kopanoar 2I-44, Nektoralik K-59, Nerlerk M-98, Orvilruk O-03 and Siulik I-05) in the northern Beaufort-Mackenzie Basin. Well logs and drill stem test data, calibrated with available cores, are analyzed for each well, with interpretations of lithology, shale content, porosity, permeability, and water saturation. Log-identified (untested) hydrocarbon reservoirs occur in sandstones and siltstones in most of the evaluated wells. Most of the tested hydrocarbon reservoirs in the northern Beaufort-Mackenzie Basin occur in porous and permeable sandstones and siltstones of the Oligocene Kugmallit Sequence. Additionally, the Nektoralik K-59 well encountered a hydrocarbon reservoir in a Pliocene limestone. Overpressure zones are identified in each of the studied wells. Most hydrocarbon reservoirs occur below or within overpressure zones. The stratigraphic framework of overpressure zones and hydrocarbon reservoirs, and observed sandstone porosity-depth trends indicate probable linkages between rapid deposition of Pliocene Iperk sediments, overpressure development, and porosity preservation.

INTRODUCTION

Numerous oil and gas fields have been discovered in the Beaufort-Mackenzie Basin and the potential for future discoveries is high (Dixon et al., 1994; 2007; Dixon, 1996; National Energy Board, 1998; 2013; Osadetz et al., 2005). Current estimates of discovered offshore resources in the Beaufort Sea are 106 million m^3 (667 million barrels) of oil and 178 billion m^3 (6.2 TCF) of gas (National Energy Board, 2014). In the northern, outer shelf part of the basin (Figure 1) there are six wells with discovered hydrocarbon accumulations in Tertiary deep-marine turbidite sandstones (Kenalooak J-94, Koakoak O-22, Kopanoar M-13, Kopanoar 2I-44, Nektoralik K-59, Nerlerk M-98), two with hydrocarbon shows (Orvilruk O-03 and Siulik I-05), and one well with a discovered hydrocarbon zone in a deep-marine Pliocene limestone (Nektoralik K-59). The geological setting is illustrated in Figure 2, and all of the wells evaluated in this study occur in similar structural and depositional settings. Eocene to Miocene turbidite sandstone reservoirs were deposited as submarine fan and basin plain deposits. Sandstones encountered in the

Koakoak, Kopanoar, Nerlerk and Siulik wells were deposited in inner fan or channel-levee settings. Sandstones in the Nektoralik, Orvilruk and Kenalooak wells were deposited in outer fan or basin-plain settings (Dixon et al., 1994; Morrell, 1995; Dixon, 1996; Dietrich et al., 2011).

Initial studies of northern basin wells (Dixon et al., 1994) identified strata with varying reservoir potential, including interchannel deposits characterized by thin-interbedded sandstones and siltstones characterized by low porosity and permeability, and less common channel sandstone deposits characterized by good porosity and permeability. Reservoir characterisation is an important element in evaluating petroleum potential in under-explored plays and prospects in the northern Beaufort-Mackenzie Basin and adjacent deep-water Canada Basin. This study provides the first comprehensive evaluation of reservoir quality in Tertiary deep-marine strata in the northern Beaufort-Mackenzie Basin. The study included petrophysical analyses of well logs, with interpretations of lithology and reservoir characteristics of sandstone and siltstone intervals. Results are summarised and graphically presented as porosity versus depth cross-plots. The log analyses also included delineation of overpressure zones interpreted in a stratigraphic context.

PETROPHYSICAL ANALYSES

Analyses of conventional wireline well logs provide information on lithology, porosity, permeability and water saturation. Possible hydrocarbon zones are identified based on selected porosity, shale content and water saturation cut-off values. Anomalous formation pressure zones are detected by integration of well log-derived shale porosity, pore pressure from mud weights, well formation testing, and well seismic velocity data (Hu et al., 2015).

Log interpretations for the study wells were complicated by three factors: (1) commonly poor borehole conditions (enlarged borehole diameters, indicated by caliper logs), with the worst borehole conditions evident in the Koakoak O-22 well; (2) limited core analysis data (core data only available for the Koakoak O-22 and Siulik I-05 wells); and (3) limited or poor quality of water analysis data (for wells with no or poor quality water analyses, data from other wells were utilized for formation water resistivity calculations).

Lithology and porosity

Lithology and porosity are known to be closely linked petrophysical parameters, since lithologic determination affects the quality of porosity estimates. Lithologies were derived from combined interpretations of gamma ray, spontaneous potential, bulk density, photoelectric index, neutron, sonic, resistivity, and caliper logs. The identified basic lithologies include sandstone, limestone, dolomite, dolomitic and/or calcareous sandstone, shale, coal, siderite, and pyrite.

Based on detailed reviews of log-derived lithology and sample and core descriptions, it is apparent that shale content is highly variable in reservoirs in the studied wells. Reservoir porosity and permeability vary significantly due to variable amounts of shale/clay in the sandstones and siltstones. Shale content or volume of shale (V_{sh}), a common indicator of reservoir quality, is estimated from well logs. In this study, the gamma ray, spontaneous potential, and neutron porosity logs were used to calculate three shale content values, with a minimum V_{sh} value selected from the calculations.

Sandstone or siltstone porosity was calculated from the sonic and density logs, with clay corrections applied for the shaly sandstone or siltstone intervals. For intervals with mixed-grain matrices such as dolomitic sandstone and dolomitic siltstone, matrix corrections were applied based on available core grain density and lithology correlations. Since shale causes higher apparent porosity on neutron logs, due to the effects of bound water, the neutron log was only used in combination with density logs for porosity calculations.

Permeability

Reservoir permeability is difficult to determine from well logs. Generally, high porosity corresponds to high permeability, but this is not always the case. Many factors in addition to overall porosity affect formation permeability, including pore size, shape, and pore or void connectivity. In fine-grained sandstone, shaly sandstone and siltstone, the individual pores and pore throats are very small and the paths available for fluid movement can be restricted. The presence of shale in reservoirs reduces permeability.

From pore to reservoir scale different direct and indirect methods including well tests, nuclear magnetic resonance well logging tools, core analysis including mercury injection, and empirical correlations are routinely employed to estimate the permeability. In this study, core

measurements from two wells allowed for establishing relationships between core porosity and permeability. Empirical relationships derived from the Timur, Tixier, or Coates equations (Schlumberger, 1989) are used to estimate maximum permeability (K) from porosity and irreducible water saturation (S_{wi}) derived from well logs. The Timur equation showed the best match to the core measurements in the Koakoak O-22 and Siulik I-05 wells.

Water saturation

Water saturation (S_w), perhaps the most challenging petrophysical calculation, is also used to determine the hydrocarbon saturation ($1-S_w$). Among the number of independent approaches to calculate S_w, the most common is the use of resistivity logs with a model (empirical or theoretical) that relates S_w to deep resistivity (R_t), formation water resistivity (R_w), porosity (ϕ), and various rock electrical properties.

The Archie water saturation equation (Archie, 1942), which relates rock resistivity to water saturation, assumes that the formation water is the only electrically conductive material in the formation. This method is applicable to clean sandstones or carbonates in which the clay-mineral content is low. In shaly rocks, R_t is suppressed due to the presence of clay minerals which affect electrical conductivity, thereby compromising the Archie estimates (water saturations are often over-estimated).

The way shaliness affects a log reading depends on the amount of shale and its physical properties. It may also depend on the way the shale is distributed in the formation (Schlumberger, 1989). In general, shaly material can be distributed in three modes within porous reservoir formations, including dispersed, laminated, and structural. Dispersed shale is the most common form in the studied wells. Shales also occur in the form of mixed dispersed and laminae in the interbedded sandstone/siltstone sections in the Kopanoar M-13 and Kopanoar 2I-44 wells. The Indonesian formula (Poupon and Leveaux, 1971) was used to calculate water saturation for the turbidite sandstones and siltstones, with the Archie equation used for limestone reservoirs with minor shale.

The inputs are effective porosity (ϕ), shale volume (V_{sh}), shale resistivity (R_{sh}), water resistivity (R_w), and deep resistivity (R_t). R_{sh} represent readings of the deep resistivity log against the adjacent shale zone of the reservoir. R_w is derived from water analysis results, or

from log analyses in clean sandstone intervals. Available R_w data from the same formation in nearby wells were used for study wells lacking R_w information. The R_w value also depends on the formation temperature that is estimated from geothermal gradient, based on log-based maximum bottomhole temperature measurements and maximum well fluid test temperatures primarily from drill stem tests (Hu et al., 2010; 2014).

Hydrocarbon zones

The identification of prospective hydrocarbon-bearing zones are based on lithology interpretation and calculations of porosity, shale content and water saturation. Cut-offs are used to define hydrocarbon zones include combinations of porosity (> 10%), water saturation (< 45%) and shale content (< 0.35).

Overpressure zones

Formation pressure is an important parameter in reservoir evaluation. Previous studies on shale compaction and overpressure in the Beaufort-Mackenzie Basin were presented by Issler and others (1992; 1994; 2002; 2011).

Overpressure significantly affects the response of conventional well logs. In this study, overpressure zones are identified from an integration of shale porosity, pore pressure from well testing, drilling mud weight, well seismic velocity and calculated sonic velocity. In the wells evaluated, overpressured shales typically exhibit well-log responses of high sonic transit times and sonic porosities, and low well seismic interval velocity. Extrapolated or original fluid testing data (such as drill stem test – DST, repeat formation test – RFT) provide quantitative formation pressure data. The fluid pressure test and mud weight data are generally consistent with the results from well log data.

Petrophysical displays

The petrophysical analyses are presented using multi-track data plots that include conventional well logs, reservoir parameters, formation lithology, core measurements, and calculated results. The log analysis profiles include nine data tracks plotted versus depth:

Track 1 displays correlative wireline logs including the gamma ray (GR), spontaneous potential (SP) and caliper logs (CALD-density caliper; CALS-sonic caliper), and the bit size

(BS). The shaded intervals indicate separation between the bit size and caliper logs, marking the sections of enlarged borehole diameter; Track 2 shows resistivity logs (deep log: ILD-deep induction or LLD-deep laterolog, medium log: ILM-medium induction or LLS-shallow induction, shallow log: SFL-spherically focused log or LL8 -8 laterolog); Track 3 shows bulk density log (RHOB), sonic transit time (DT), neutron porosity log with sandstone calibration (NPss, if available), and photoelectric index (PEF, if available); Track 4 displays the calculated porosity curve (PHIE), and core porosity data (PHIcore, where present); Track 5 shows calculated water saturation (S_w); Track 6 displays calculated permeability (K), and core permeability data (Kcore, if available); Track 7 displays the log-determined lithology; Track 8 indicates potential hydrocarbon zones with noted cut-offs (porosity > 10%, water saturation < 45%, shale content < 0.35); and Track 9 displays drill stem test (DST) data, if available.

RESERVOIR EVALUATIONS

The stratigraphic depth tops for the eight wells are shown in Table 1. Most of the wells penetrated Pliocene to Oligocene strata (Iperk to Kugmallit sequences), with four wells (Kopanoar 2I-44, Kopanoar M-13, Nerlerk M-98, and Orvilruk O-03) reaching Eocene strata of the Richards and Taglu sequences. The deepest well (Nerlerk M-98) reached a depth of 4890 m. The focus of this study is on the lower Pliocene to Eocene sections that contain tested and interpreted hydrocarbon zones.

Table 1. Stratigraphic tops and total drill depths (metres below KB) in the eight wells evaluated in this study. TD - Total Depth, TVD - True Vertical Depth (for deviated wells).

Age	Sequence Top (m)	**Kenalooak J-94**	**Koakoak O-22**	**Kopanoar 2I-44**	**Kopanoar M-13**	**Nektoralik K-59**	**Nerlerk M-98**	**Orvilruk O-03**	**Siulik I-05**
Pliocene	Iperk	80	60	70	69	77	65	73	64
Miocene	Akpak		2814	2489	2557	2262	2843	2085	
	Mackenzie Bay			2605	2682	2640 (2637)		2325	
Oligocene	Kugmallit	3823	3052	2655	2785		3135	3030	3007
Eocene	Richards			3915 (3910)	4289 (4279)		4420 (4408)		
	Taglu							3375	
	TD (TVD)	4569 (4565)	4365 (4359)	4015 (4009)	4320 (4310)	2790 (2787)	4940 (4890)	3912 (3893)	4824 (4803)

Kenalooak J-94

The Kenalooak J-94 well was drilled from 1979 to 1981 (multi-season drilling), to a total depth of 4565 m (TVD). Due to separate logging runs in different years, the density logs do not match the electrical and sonic logs, and resistivity logs were only acquired in the second year of drilling. Density-neutron log sets are shifted downward by 1 metre for the interval from 3948 to 4040 m, and shifted upward by about 3.7 m for the following interval (4040 m - TD). Detailed deviation survey data is incomplete for the well and measured depths cannot be converted to true vertical depths.

The Kenalooak well encountered hydrocarbon zones in Oligocene sandstones in the Kugmallit Sequence (Figure 3). A gas zone (4490-4501 m) occurs in sandstones with log-measured porosity of 25%, permeability of 200 mD, and gas saturation of 80%. The data indicate good reservoir quality. A drill stem test of this interval (DST#2) flowed gas at a rate of 113,000 m^3/d (3.9 MMcf/d). Potential hydrocarbon zones are identified in other parts of the section, including a sandstone interval (4468-4474 m) with average porosity of 22% and permeability of 80 mD.

Koakoak O-22

Dome Hunt Gulf Koakoak O-22 well was drilled in 1979, with re-entries in 1980 and 1981, to a total depth of 4365 m. The caliper logging curves indicate enlarged borehole conditions from surface to 3595 m, resulting in suspect log readings due to fluid invasion. Core interval depths needed to be shifted to log curves, due to mismatch between log character and core lithology.

Reservoir properties evaluated based on core analyses (Figure 4) and well log data indicate that the Koakoak well encountered hydrocarbon zones in Oligocene sandstones in the Kugmallit Sequence (Figure 5). The lower part of the section contains the main hydrocarbon zone, a 30 m thick sandstone (3470-3500 m). Log and core data indicate this sandstone interval has high porosity (23-33 %) and permeability (61-2500 mD; Figures 4 and 5). Drill stem tests of the zone recovered 130-410 m of clean oil and 51-257 m of water (DST#4 and DST#4A), and flowed gas at maximum rate of 544,000 m^3/d (6 MMcf/d from DST#4; 19 MMcf/d from DST#4A). A third drill stem test of an overlying zone (DST#5; 3308-3330 m) recovered 30 m of oil and flowed gas

at 207,000 m^3/d (7 MMcf/d). This hydrocarbon zone is about 10 m thick, with average porosity of 22% and permeability of 100 mD. Log analyses indicate the presence of other thin hydrocarbon zones, characterized by good porosity (20-30%) and permeability (>100 mD) within the Kugmallit sandstones.

Kopanoar M-13

Dome Gulf Hunt Kopanoar M-13 well was drilled from 1976 to 1979, to a total depth of 4320.2 m. The well penetrated Pliocene to Eocene strata. Drill stem tests in 1979 recovered significant quantities of oil and gas from sandstones in the Oligocene Kugmallit Sequence. The M-13 well was the first major oil discovery in the deep-marine (turbidite) play in the northern part of the basin.

Conventional well logs were acquired for the entire well. Among the three porosity logs, the density log was utilised, because high silt content in some sandstones adversely affects porosity calculations from neutron and sonic logs, even after a shale correction is applied.

Formation water resistivity obtained from water analyses is used for calculations of water saturation in various sequences, with temperature corrections based on formation temperature data and geothermal gradient (Hu et al., 2010 and Hu et al., 2014).

Hydrocarbon zones occur in channel sandstones from 3500 to 3650 m (Figure 6). The sandstones have fair to good porosity and permeability (15 to 30 % and 5 to 300 mD, respectively). The main hydrocarbon zone is in a 19 m thick sandstone (3536.6 - 3555.5 m) that flowed oil and gas (DST#5A) at maximum rates of 968 m^3/d (6088 bbl/d) and 138,000 m^3/d (4.8 MMcf/d). Other significant hydrocarbon recoveries in the section included DST#4 (3578 - 3590.2 m; oil at 67 m^3/d and gas at 4330 m^3/d), and DST#6 (3515.6 - 3524.7 m; oil at 444 m^3/d oil and gas at 79,900 m^3/d).

Kopanoar 2I-44

The Dome Gulf Hunt Kopanoar 2I-44 well was the step-out well to the Kopanoar M-13 discovery. The 2I-44 well was drilled in 1980 to a depth of 3164 m, and was re-entered in 1981 to reach a total depth of 4015 m. The 2I-44 well penetrated Pliocene to Eocene strata, encountering oil and gas zones in the Oligocene and Eocene sequences. The hydrocarbon flow rates were lower than in the Kopanoar M-13 well. Although drilled on the same structure 4 km

apart, well correlation and seismic data suggests stratigraphic discontinuity and/or compartmentalization between oil/gas reservoirs encountered by two Kopanoar wells (Morrell, 1996).

Conventional well logs were acquired in the 2I-44 well, from 425 m to 3656 m, but no complete log data set was acquired from 3656 m to 4014 m. Available well logs with measured depths were converted to true vertical depths.

Five hydrocarbon zones are identified in the Oligocene Kugmallit Sequence in the 2I-44 well (zones A to E; Figure 7). The thickest hydrocarbon zone (A; 2960 - 3060 m) occurs in sandstones and silty sandstones, with porosity of 15 to 25 % and permeability of 5 to 100 mD. DST#8 in the upper part of this zone recovered oil and gas at maximum rates of 21 m^3/d (735 bbl/d) and 30,000 m^3/d (1 MMcf/d). The other hydrocarbon zones (B to E) all occur in intervals of thin sandstones and siltstones. Individual sandstone beds have variable porosity and permeability (up to 20% and 50 mD, respectively). The best hydrocarbon recovery in the well came from the upper part of Zone C. A thin sandstone in this zone (3195 - 3207 m) tested oil and gas (DST#6) at rates of 307 m^3/d (1931 bbl/d) and 75,800 m^3/d (2.6 MMcf/d).

The 2I-44 well also encountered a hydrocarbon zone in Eocene strata. The thin reservoir sandstones in this zone (3912 - 3936 m) have porosity of 15 to 20 % and permeability of 40 to 100 mD. A test of the interval (DST#1) recovered gas at a maximum rate of 290,000 m^3/d (10 MMcf/d).

Nektoralik K-59

The Dome Hunt Nektoralik K-59 well was drilled from 1976 to 1977 to a total depth of 2790 m. Oil and gas were discovered in Pliocene and Miocene strata. The quality of well log data are compromised in intervals with an enlarged borehole.

Hydrocarbon zones occur in sandstones and in a limestone bed of the lower (Pliocene) Iperk Sequence (Figure 8). The sandstones are characterized by good porosity and permeability, up to 34% and 200 mD, respectively. The main hydrocarbon zone in the limestone unit is characterised by good porosity (20 to 25 %) and fair permeability (1 to 10 mD). A test of the 3 m thick limestone interval (DST#7, 2258.6-2261.6m) recovered oil and gas at rates of 146 m^3/d (900 bbl/d) and 147,000 m^3/d (5 MMcf/d).

The K-59 well also encountered hydrocarbon zones in Miocene sandstones and siltstones within the Mackenzie Bay Sequence. These clastic reservoirs have good porosity (20 to 33%) and fair to good permeability (20 to 300 mD). Drill stem tests of two intervals (DST#1, 2695-2701.1 m, and DST#2, 2651.8-2685.3 m) recovered oil and gas at rates of 183 and 25 m^3/d (1151 and 157 bbl/d) and 30,000 and 146,000 m^3/d (1 and 5 MMcf/d), respectively.

Nerlerk M-98

Dome Nerlerk M-98 was drilled from 1977 to 1979, to a total depth of 4940 m (4890 m TVD). The well penetrated Pliocene to Eocene strata, with hydrocarbon zones encountered in several sections. Conventional well logs were run for the entire well, with caliper logs indicating poor borehole conditions over large intervals in the Oligocene section.

The main hydrocarbon zone occurs in a section of interbedded sandstones and shale in the upper Kugmallit Sequence (Figure 9). The sandstone is characterized by good porosity (20-30 %) and variable permeability (20-500 mD). A drill stem test of the upper part of this section (DST#8; 3135-3172 m) flowed oil at maximum rate of 64 m^3/d (402 bbl/d). Three other tests of sandstones in the Kugmallit and overlying Akpak sequences (DST#4A, 7, 9) recovered small amounts of oil and water. Although hydrocarbon recoveries were low, the sandstones in these tested intervals have fair to good reservoir quality (porosity and permeability up to 25 % and 100 mD, respectively).

Orvilruk O-03

The Dome Superior Orvilruk O-03 well was drilled from 1980 to 1982, to a total depth of 3912 m (3893 m TVD). The well penetrated Pliocene, Miocene, Oligocene and possibly Eocene strata. Conventional well logs were run for the entire well, with caliper logs indicating generally poor borehole conditions through most intervals of the well.

A gas show was encountered in the lower Kugmallit Sequence and potential (untested) hydrocarbon zones are indicated by log analyses (Figure 10). The gas zone (small volume gas flow in DST#1) occurs in a thin sandstone in the lower Kugmallit Sequence characterized by porosity and permeability up 25% and 200 mD, respectively. Other potential hydrocarbon zones occur in the Kugmallit and Mackenzie Bay sequences, with Miocene sandstone reservoirs

characterised by good to excellent porosity and permeability (up to 30% and 1000 mD, respectively).

Siulik I-05

The Dome Siulik I-05 well was drilled in 1983 and 1984, to a total depth of 4824 m (4803 m TVD). The well penetrated Pliocene and Oligocene strata. A complete conventional logging set was run from 698 m to the well bottom. Sidewall cores were acquired through two intervals. Oil and gas shows were encountered in the Kugmallit Sequence.

Core#1 (3637-3993.5 m; Figure 11) includes 36 sidewall samples of siltstones, with measured porosity by length of 16 to 25 % m (sample lengths are unknown), and one measured permeability (2.5 mD; permeability values are low (<1 mD) for 35 other samples). Figure 11 illustrates the distributions of core porosity by length (average 20.6 % m, median 20.7 % m) and grain density (average of 2715 kg/m^3, median 2715 kg/m^3). The higher core grain densities are related to the presence of siderite and pyrite. Oil staining was documented in the well history report.

Core#2 (4065.9-4699.9 m; Figure 12) includes 19 sidewall samples of sandstones, with good porosity (average 20%, maximum 25.2%) and good permeability (average 136 mD, median 42 mD, maximum 850 mD). Figure 12 illustrates the distributions of core porosity and permeability, with a quantitative linear relationship between the two measurements at semi-logarithm axis. The core and log measured reservoir parameters in the Siulik well are generally comparable, though with an apparent trend for slightly higher core-measured porosity and permeability values (Figure 13).

A drill stem test in part of the Core#1 siltstone interval in the upper Kugmallit Sequence (DST#2; 3955-3976 m) flowed oil at 10.2 m^3/d (64 bbl/d; Figure 13). A test of multiple zones in the lower Kugmallit (DST#1; 4053-4272 m), including the Core#2 sandstone interval, recovered minor amounts of oil and water, and flowed gas at 10,000 m^3/d (0.35 MMcf/d).

OVERPRESSURE

A composite plot, consisting of shale sonic porosity, well seismic interval velocity and sonic velocity, pore pressures from well tests, drilling mud weights, and borehole temperatures, is used to display overpressure identification (Figure 14).

Based on an integrated interpretation, overpressure zones are identified in all of the eight evaluated wells (Figure 14a for Kenalooak J-94 and Koakoak O-22 wells; Figure 14b for Kopanoar M-13 and 2I-44 wells; Figure 14c for Nektoralik K-59 and Nerlerk M-98 wells; Figure 14d for Orvilruk O-03 and Siulik I-05 wells). The top of overpressure zones are delineated by abrupt downward increases in sonic porosity and decreases in seismic interval and sonic velocities. Well drilling mud weights as indicated by mud pressure readings were increased at or above the top of overpressure zones, with drill stem test data documenting the elevated formation pressures.

DISCUSSION

Petrophysical evaluations of wireline well logs indicate porous and permeable sandstones are common in Tertiary deep-marine strata in the northern Beaufort-Mackenzie Basin. The eight evaluated wells indicate a general trend of decreasing sandstone porosity with depth (Figures 15 and 16). At the depths commonly explored for hydrocarbon reservoirs in this part of the basin (2000 to 5000 m), sandstone porosity is typically good to excellent (median values from 12 to 22%, maximum values from 20 to 30%). Abrupt increases of sandstone porosity at certain depths commonly reflect the top of overpressure zones.

Figure16 shows a comparison of the porosity-depth trends for sandstones that have different shale content ranges. It is evident that widespread variable shale contents in sandstones reduces porosity to lower values (Figure 16b). Detected possible overpressure zones occur in two depths ranges, distributing from 2000 to 3250 m in the shallow interval and from 3970 to 4300 m in the deep interval (pink coloured areas in Figure 16a).

Most of the discovered and potential hydrocarbon zones occur in the Oligocene Kugmallit Sequence. There is no obvious difference in reservoir quality between Oligocene slope-inner fan channel sandstones encountered in the Kopanoar, Nerlerk, Koakaok and Siulik wells, and outer

fan-basin plain sandstones encountered in the Kenalooak well. The analysed data indicate that turbidite sandstones appear to be good exploration (reservoir) targets for the northern Beaufort-Mackenzie and southern Canada basins. Based on the limited observations in the Kopanoar wells, reservoir continuity may be an exploration risk factor in areas with channel-levee depositional systems.

Overpressure zones occur in all wells in the northern Beaufort-Mackenzie Basin. The depth and stratigraphic distribution of overpressure zones and hydrocarbon zones are illustrated in well cross-sections (A-A' and B-B'; Figure 17). All overpressure zones occur below depths of 2000 m, with the top of a regional overpressure zone occurring at or near the base of the Pliocene Iperk Sequence. In four wells (Kopanoar 2I-44, Orvilruk, Siulik and Nerlerk), two overpressure zones are detected, with the top of the deeper zone occurring at variable depths and stratigraphic levels. The stratigraphic framework of overpressure zones indicates a probable linkage between deposition of Pliocene strata (Iperk Sequence) and overpressure development. In the northern Beaufort-Mackenzie Basin, Pliocene sedimentation rates were much higher than Miocene sedimentation rates (McNeil et al., 2001). Rapid sedimentation is a common cause of overpressure development. As shown in Figure 17, all of the discovered and log-indicated hydrocarbon zones occur below the top of one or more overpressure zones.

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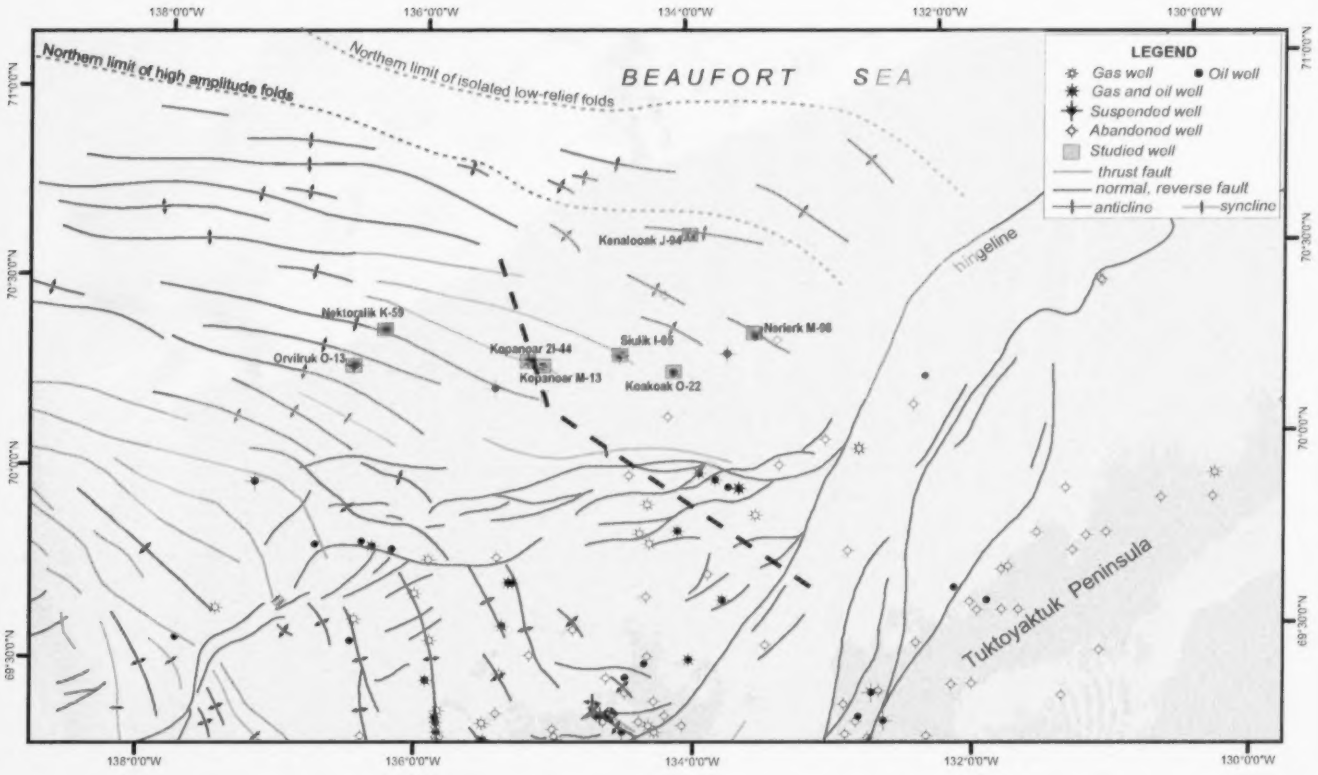

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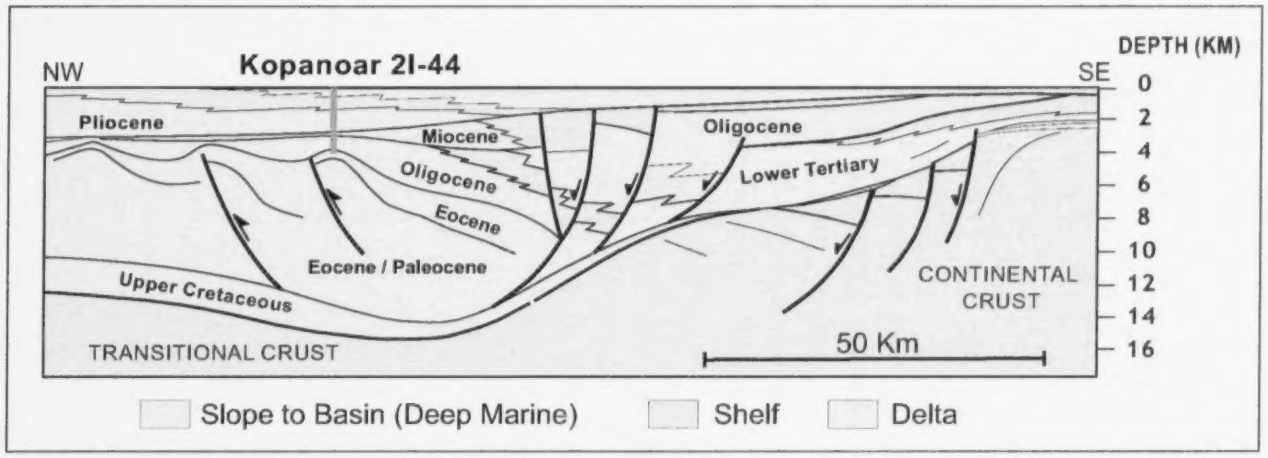

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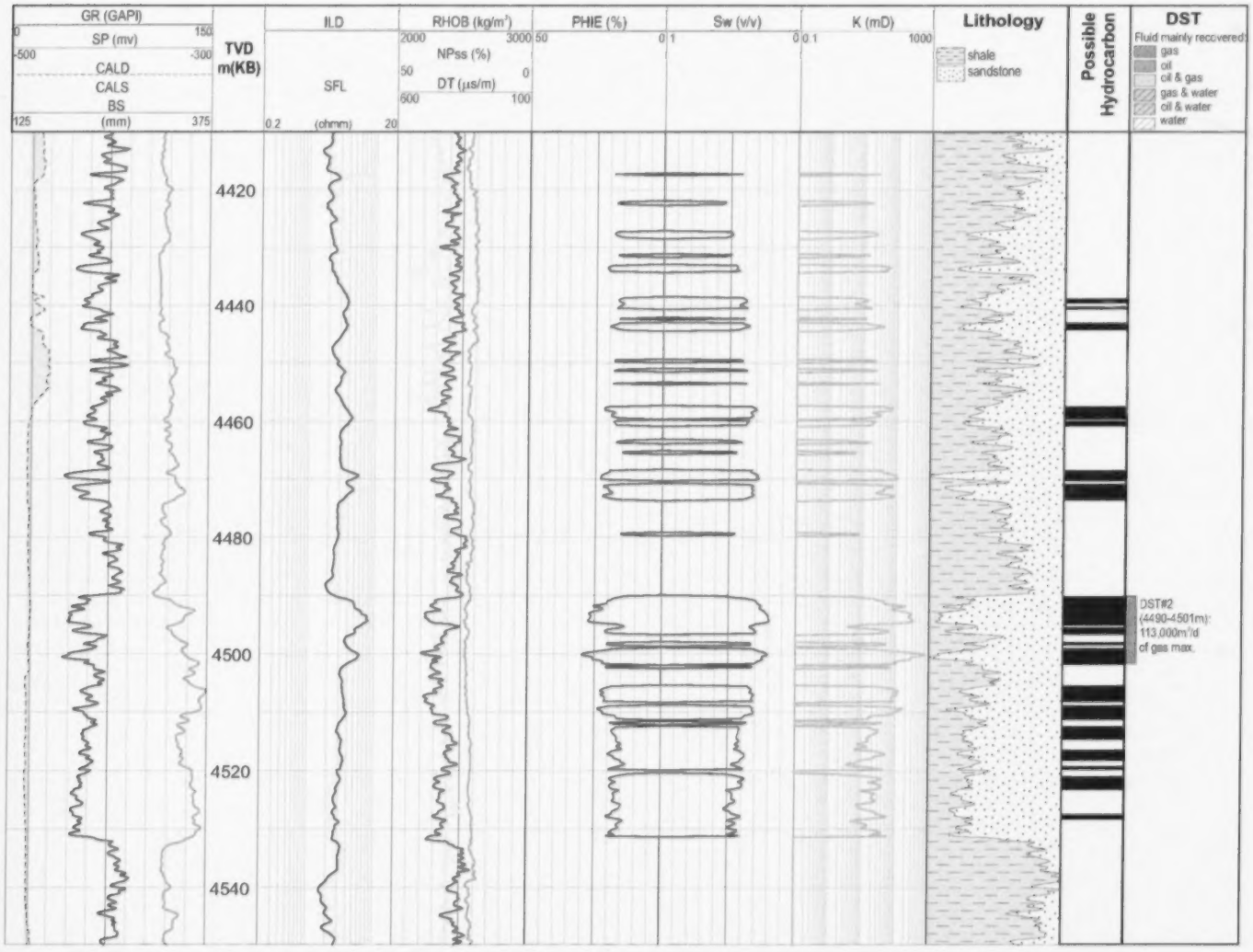


GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, SFL-spherically focused resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PHIE-calculated effective porosity, S_w - calculated water saturation, K - calculated maximum permeability.

Figure 3. Composite log and petrophysical analyses including lithology interpretation and identified potential hydrocarbon zones in the Oligocene Kugmallit Sequence penetrated by Kenalooak J-94 well.

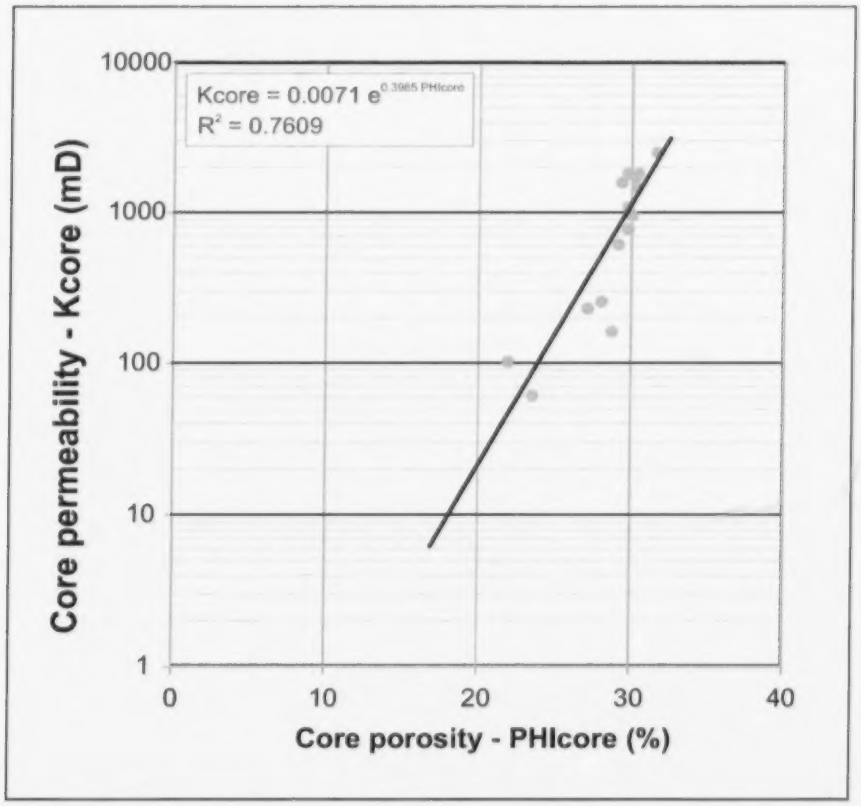
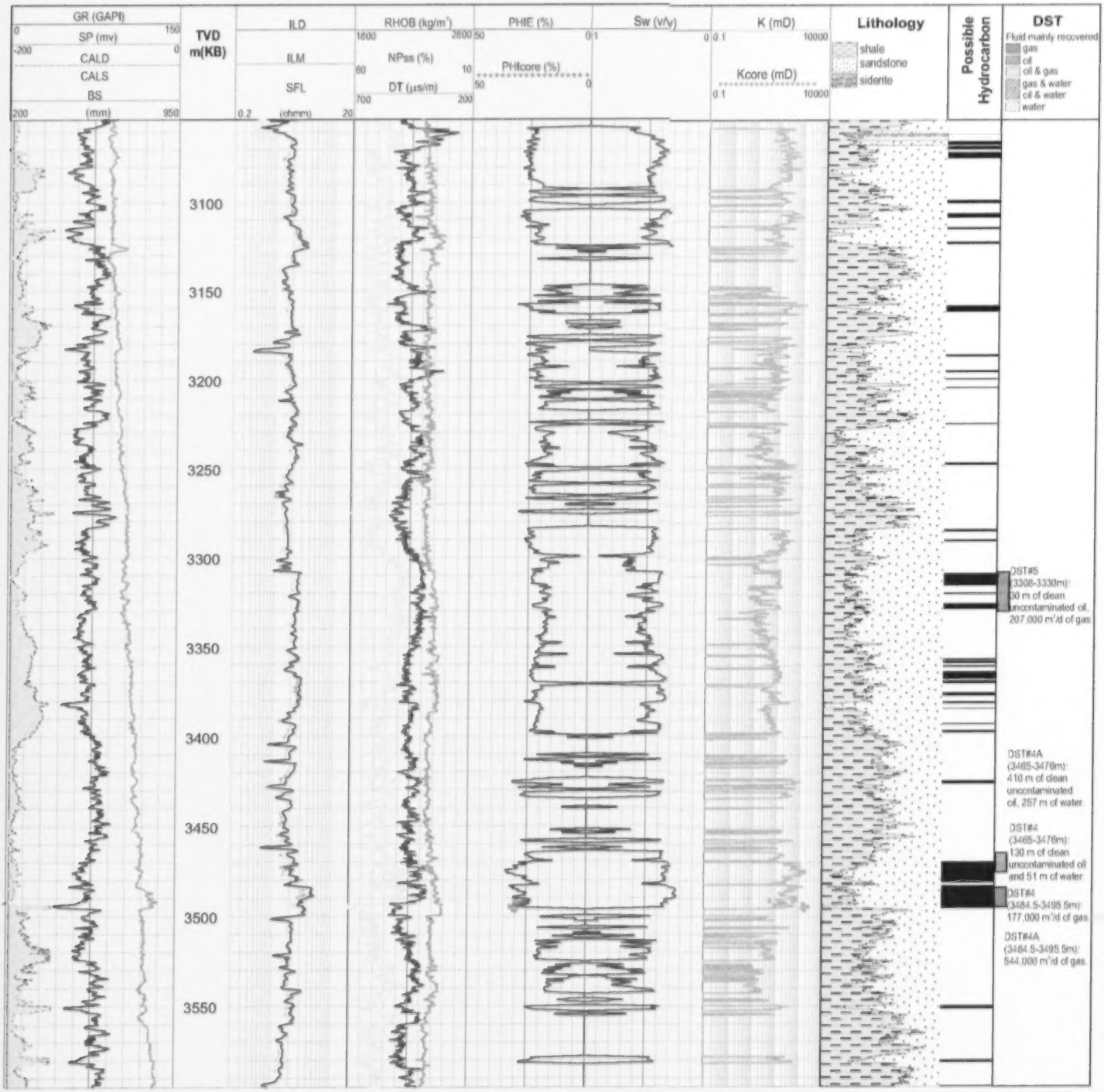
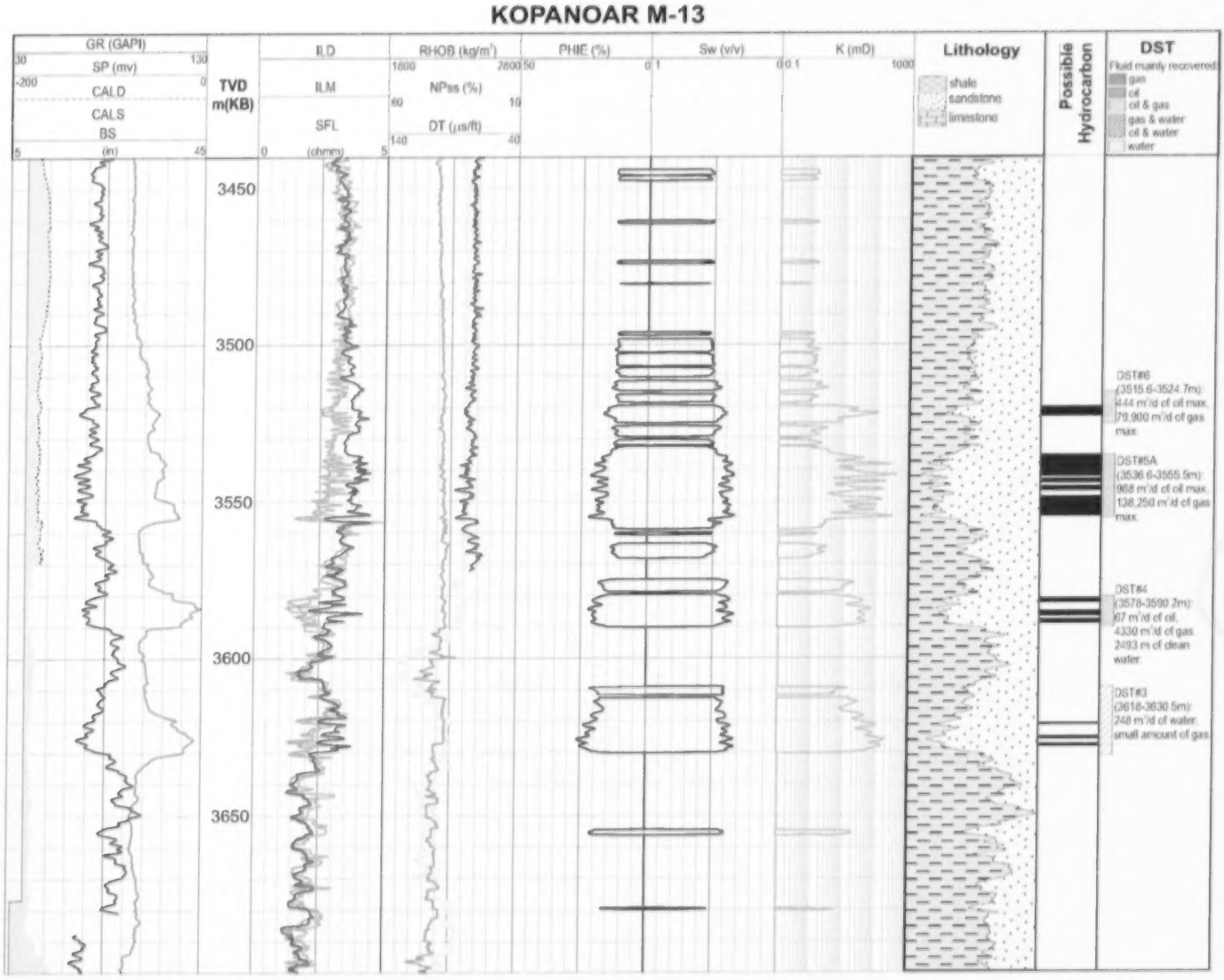


Figure 4. Porosity-permeability core measurements cross-plot for a fine to medium-grained sandstone in the Kugmallit Sequence (3490.9 - 3499.6 m) in the Koakoak O-22 well. The data indicate a linear relationship between porosity and permeability at semi-logarithm axis.



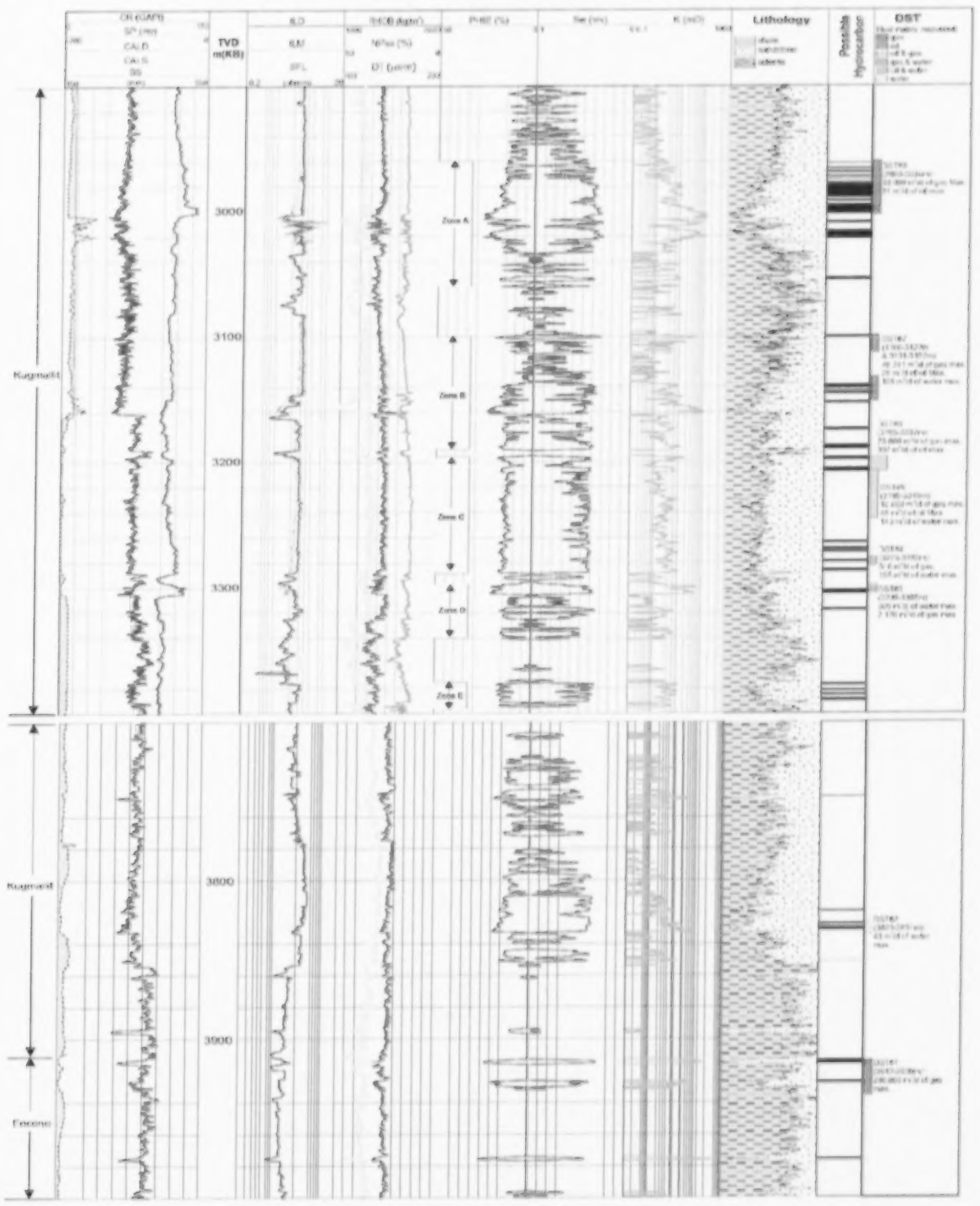
GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, SFL-spherically focused resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PHIE-calculated effective porosity, PHIcore-core porosity, S_w-calculated water saturation, K-calculated maximum permeability, Kcore-core permeability.

Figure 5. Composite log with core data and petrophysical analyses including lithology interpretation and potential hydrocarbon zones encountered in the Kugmallit Sequence by the Koakoak O-22 well.



GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, SFL-spherically focused resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PHIE-calculated effective porosity, S_w-calculated water saturation, K-calculated maximum permeability.

Figure 6. Composite log and petrophysical analyses including lithology interpretation and potential hydrocarbon zones encountered in the Kugmallit Sequence by the Kopanoar M-13 well.



GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, SFL- spherically focused resistivity, RHOB-bulk density, DT- sonic transit time, NPss- sandstone calibrated neutron porosity, PHIE-calculated effective porosity, S_w- calculated water saturation, K-calculated maximum permeability.

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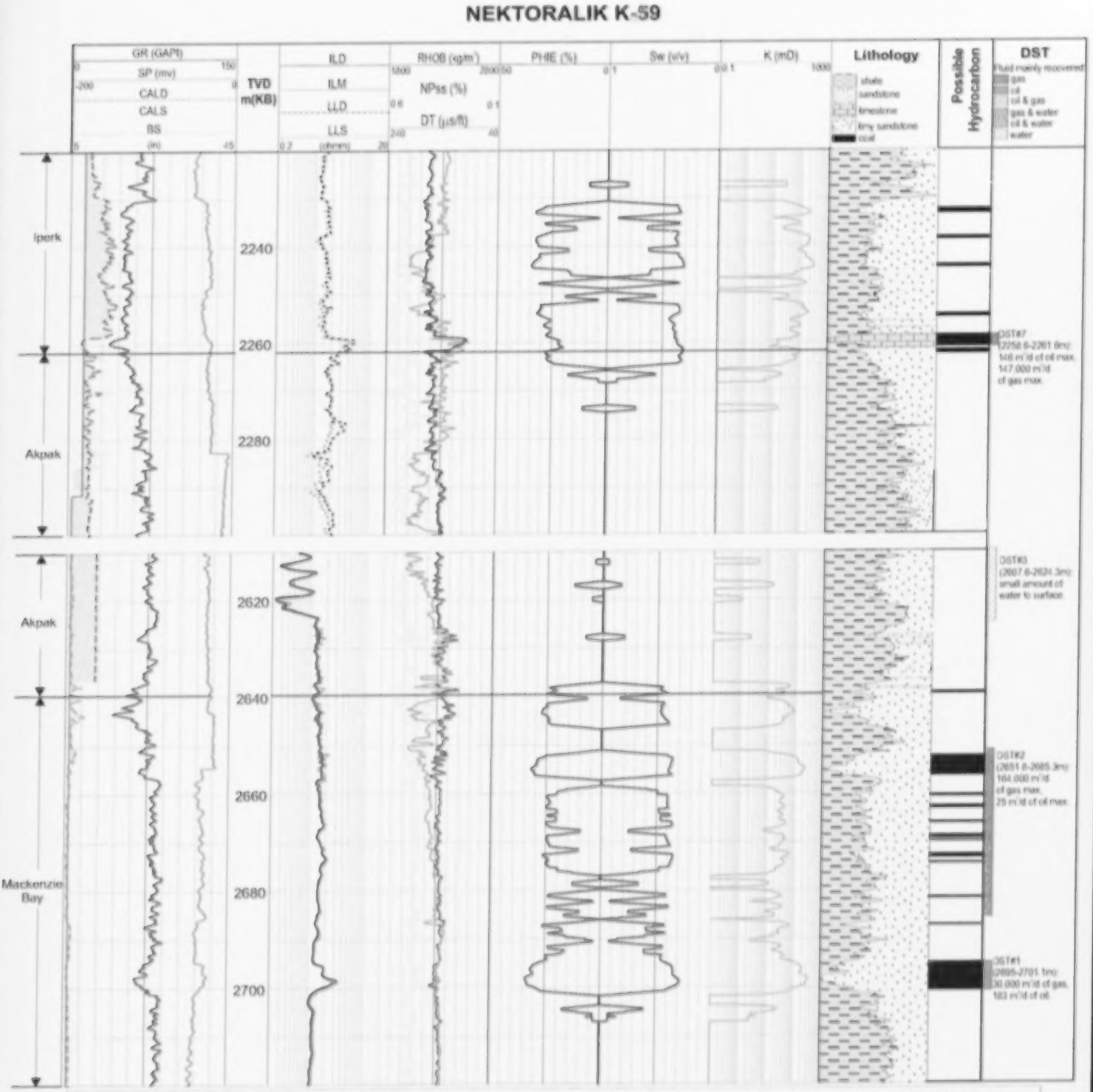
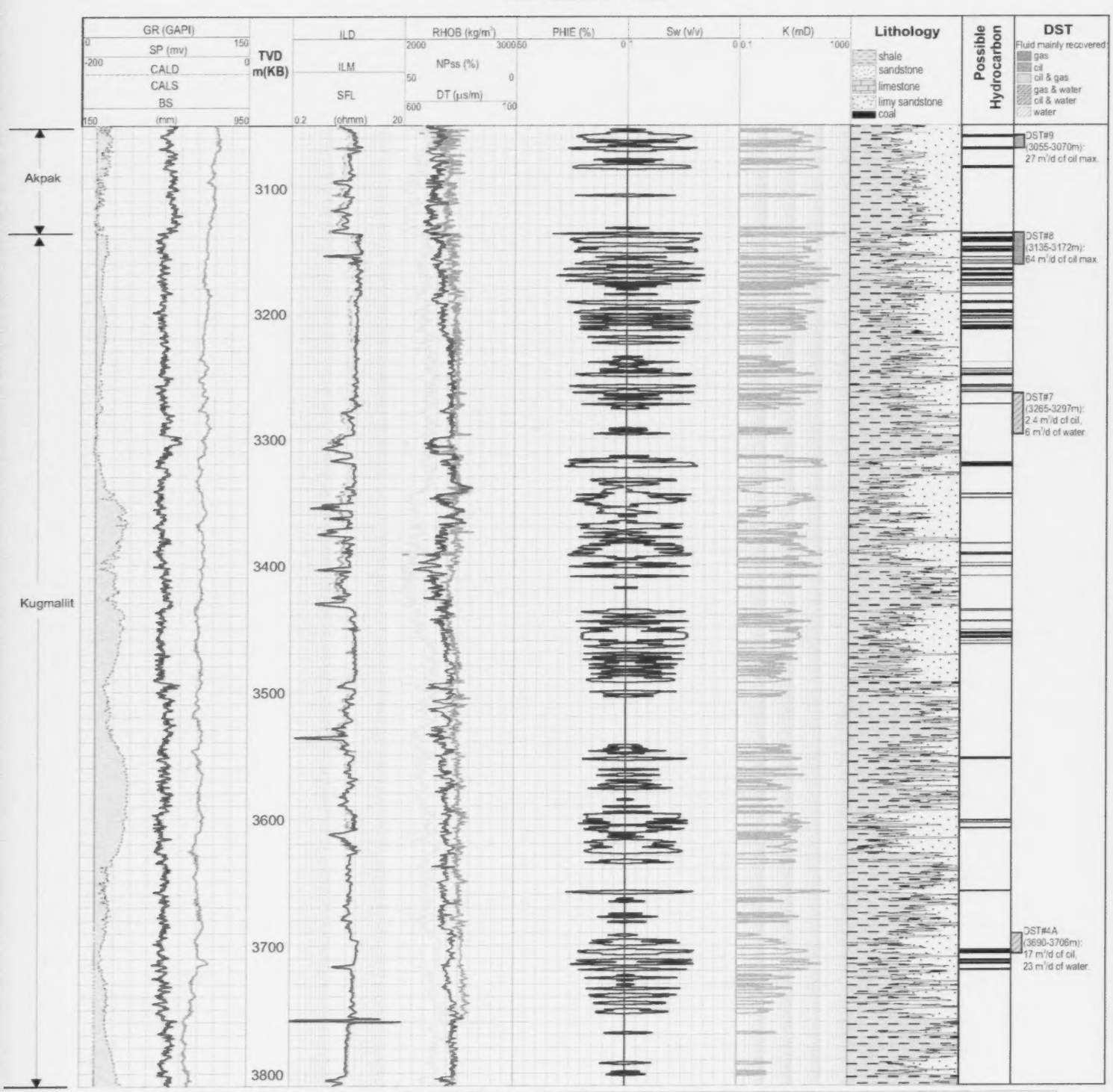


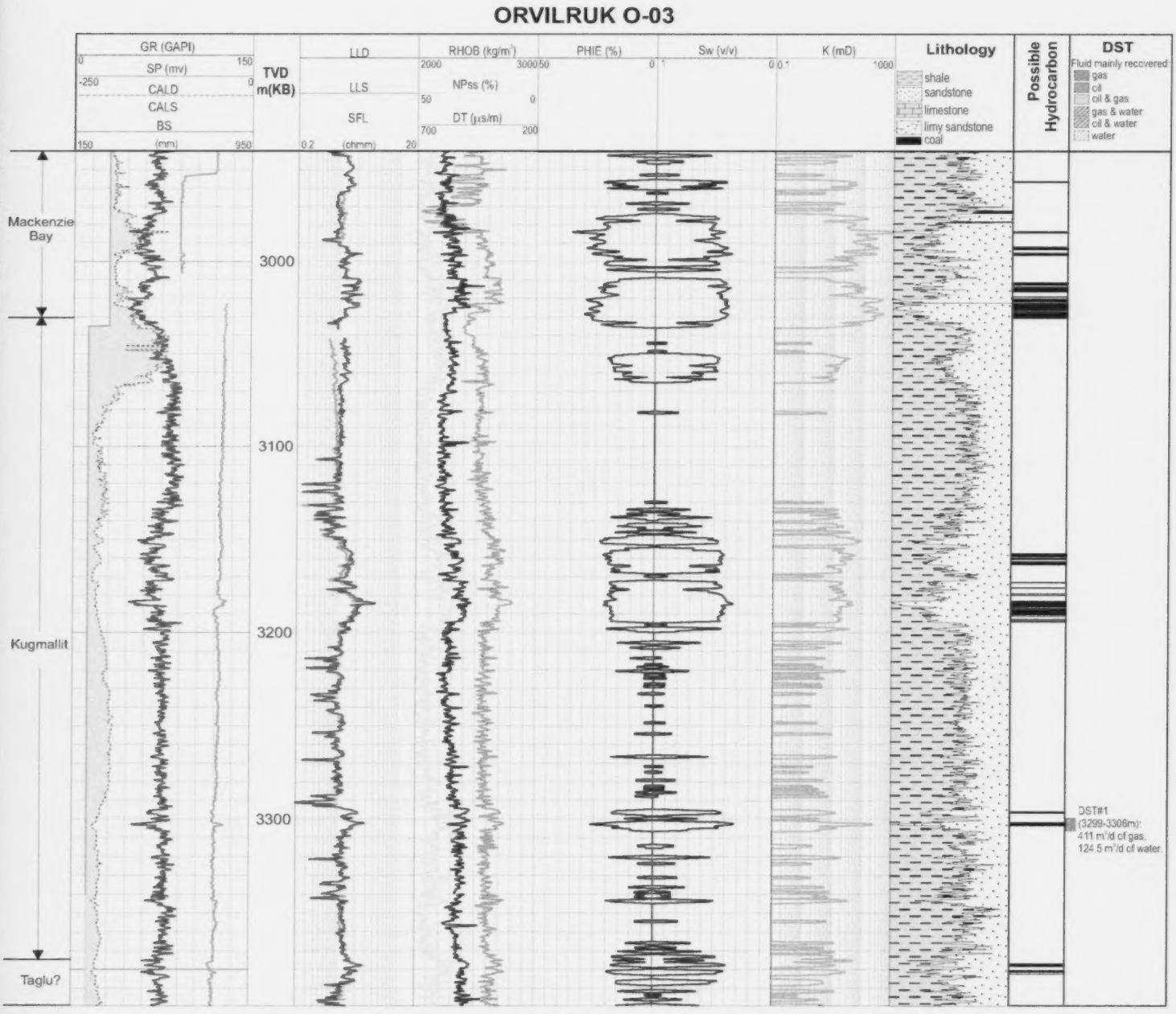
GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, LLD-deep laterolog resistivity, LLS-shallow laterolog resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PHIE-calculated effective porosity, S_w- calculated water saturation, K-calculated maximum permeability.

Figure 8. Composite log and petrophysical analyses including lithology interpretation and potential hydrocarbon zones encountered by the Nektoralik K-59 well. Note: top panel include data for the lower Iperk and upper Akpak sequences; the bottom panel include data for the lower Akpak and Mackenzie Bay sequences.



GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, SFL-spherically focused resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PHIE-calculated effective porosity, S_w- calculated water saturation, K-calculated maximum permeability.

Figure 9. Composite log and petrophysical analyses including lithology interpretation and potential hydrocarbon zones in the Kugmallit and lower Akpak sequences encountered by the Nerlerk M-98 well.



GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, SFL-spherically focused resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PHIE-calculated effective porosity, S_w- calculated water saturation, K-calculated maximum permeability.

Figure 10. Composite log and petrophysical analyses including lithology interpretation and possible hydrocarbon zones in the Mackenzie Bay, Kugmallit and Taglu (?) sequences encountered by the Orvilruk O-03 well.

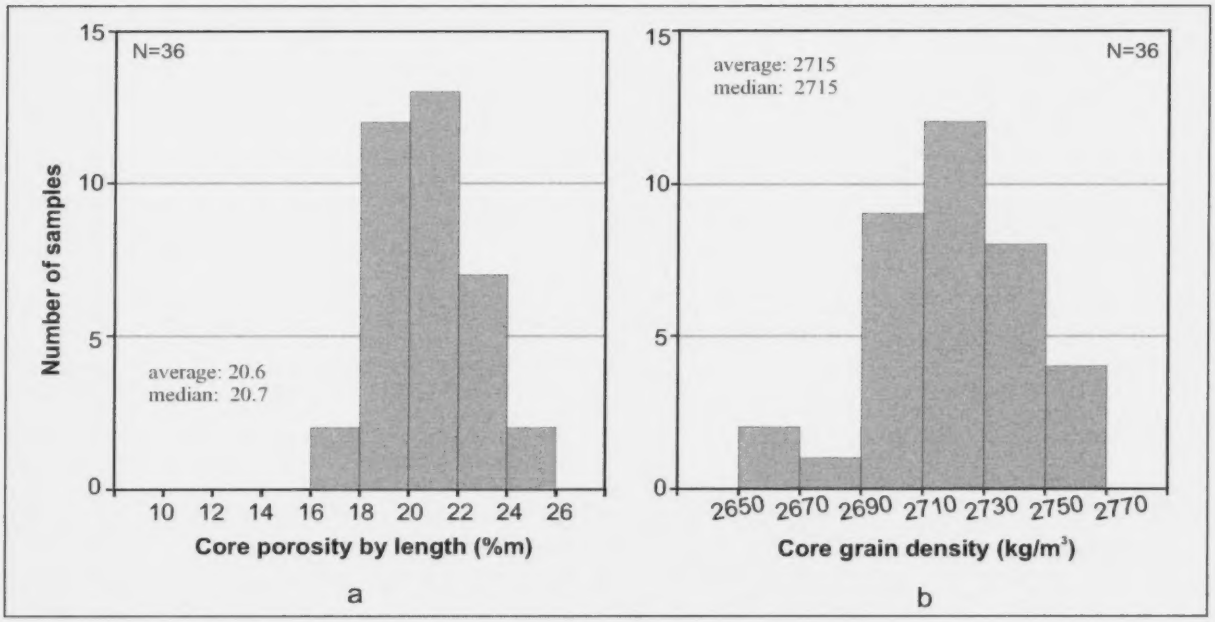
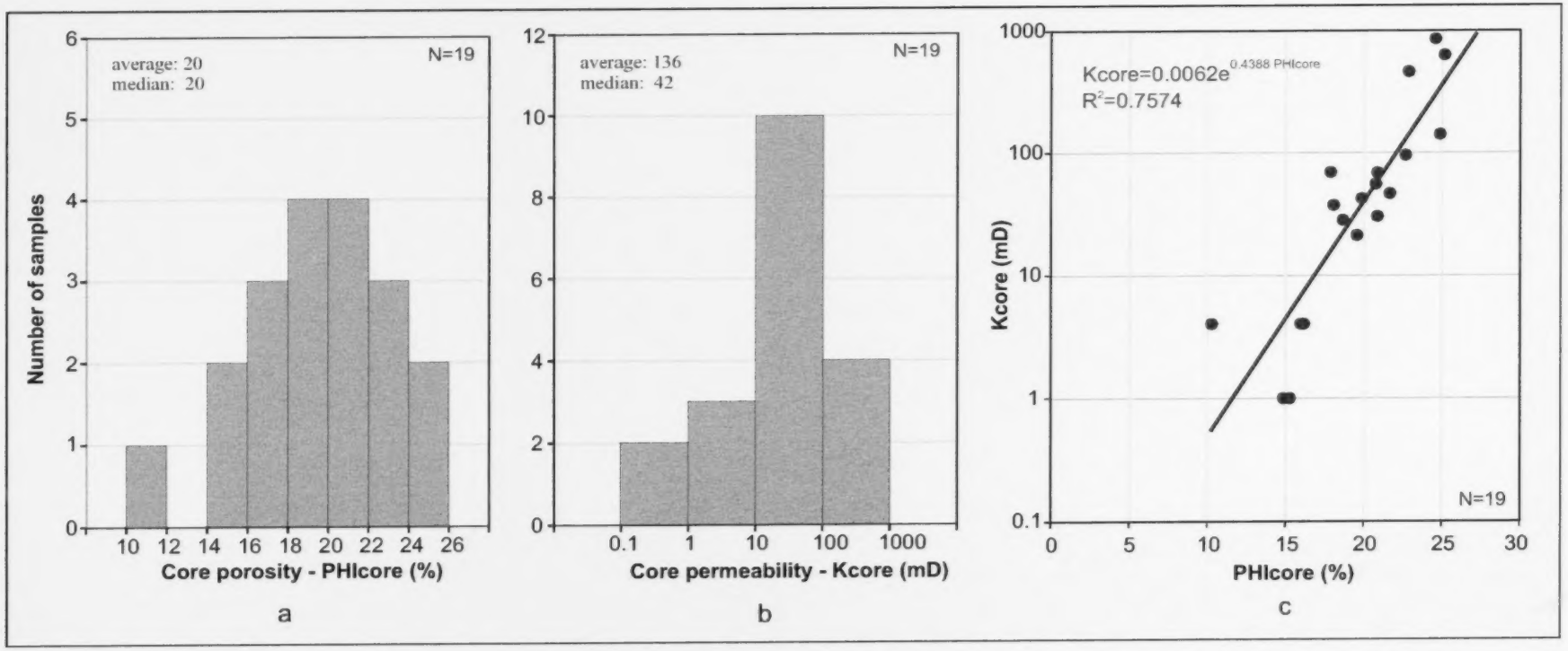


Figure 11. Distributions of core porosity by sample length (a) and grain density (b) from Core#1 siltstone samples (3637-3993.5 m) in the Siulik I-05 well. N: total number of sidewall samples.



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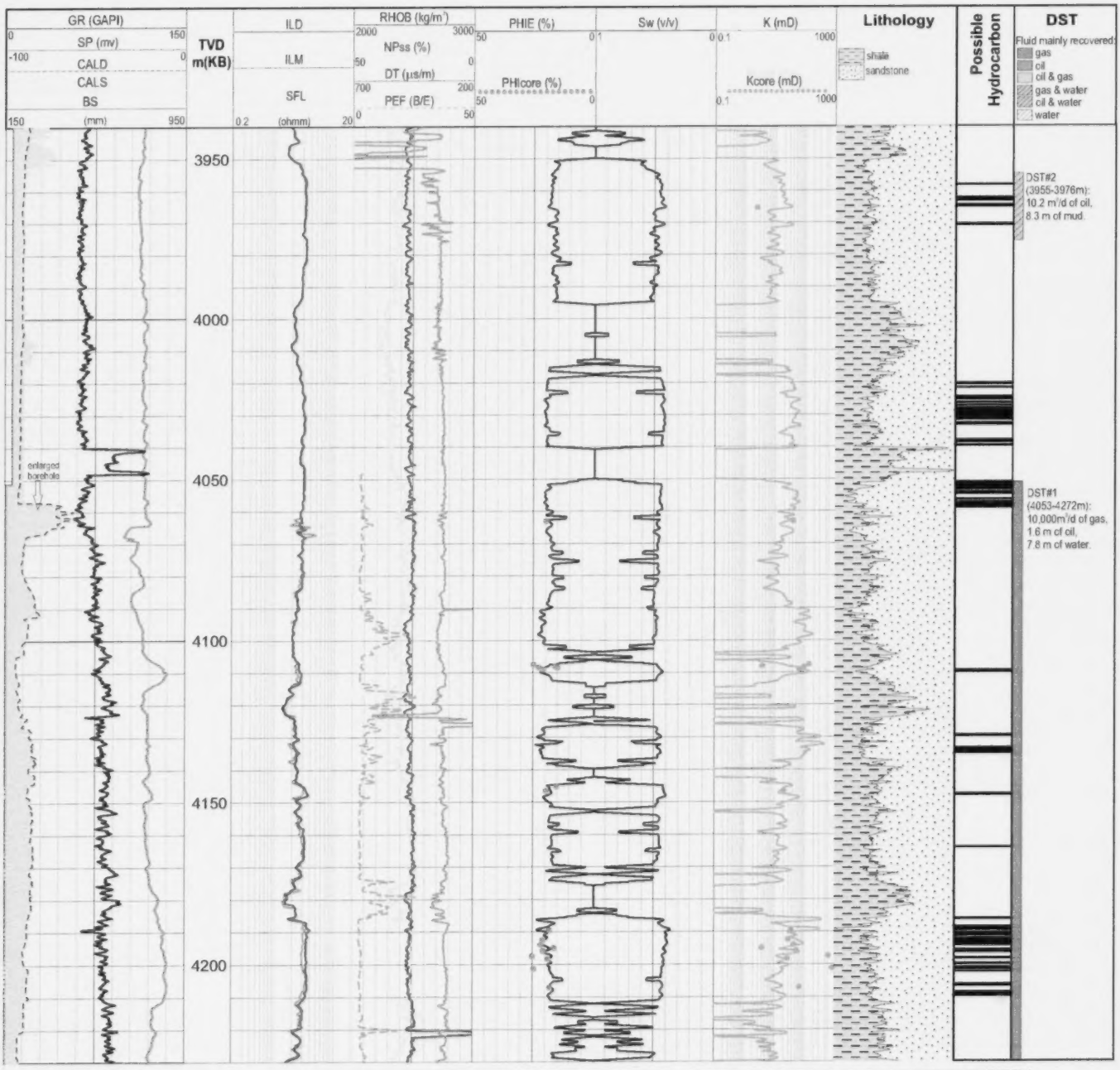


GR-gamma ray, SP-spontaneous potential, BS- bit size, CALD-density caliper, CALS-sonic caliper, ILD-deep induction resistivity, ILM-medium induction resistivity, SFL-spherically focused resistivity, RHOB-bulk density, DT-sonic transit time, NPss-sandstone calibrated neutron porosity, PEF-photo electric factor, PHIE-calculated effective porosity, PHIcore-core porosity, S_w- calculated water saturation, K-calculated maximum permeability, Kcore-core permeability.

Figure 13. Composite log, core data, and petrophysical analyses including lithology interpretation and possible hydrocarbon zones in the Kugmallit Sequence encountered by the Siulik I-05 well.

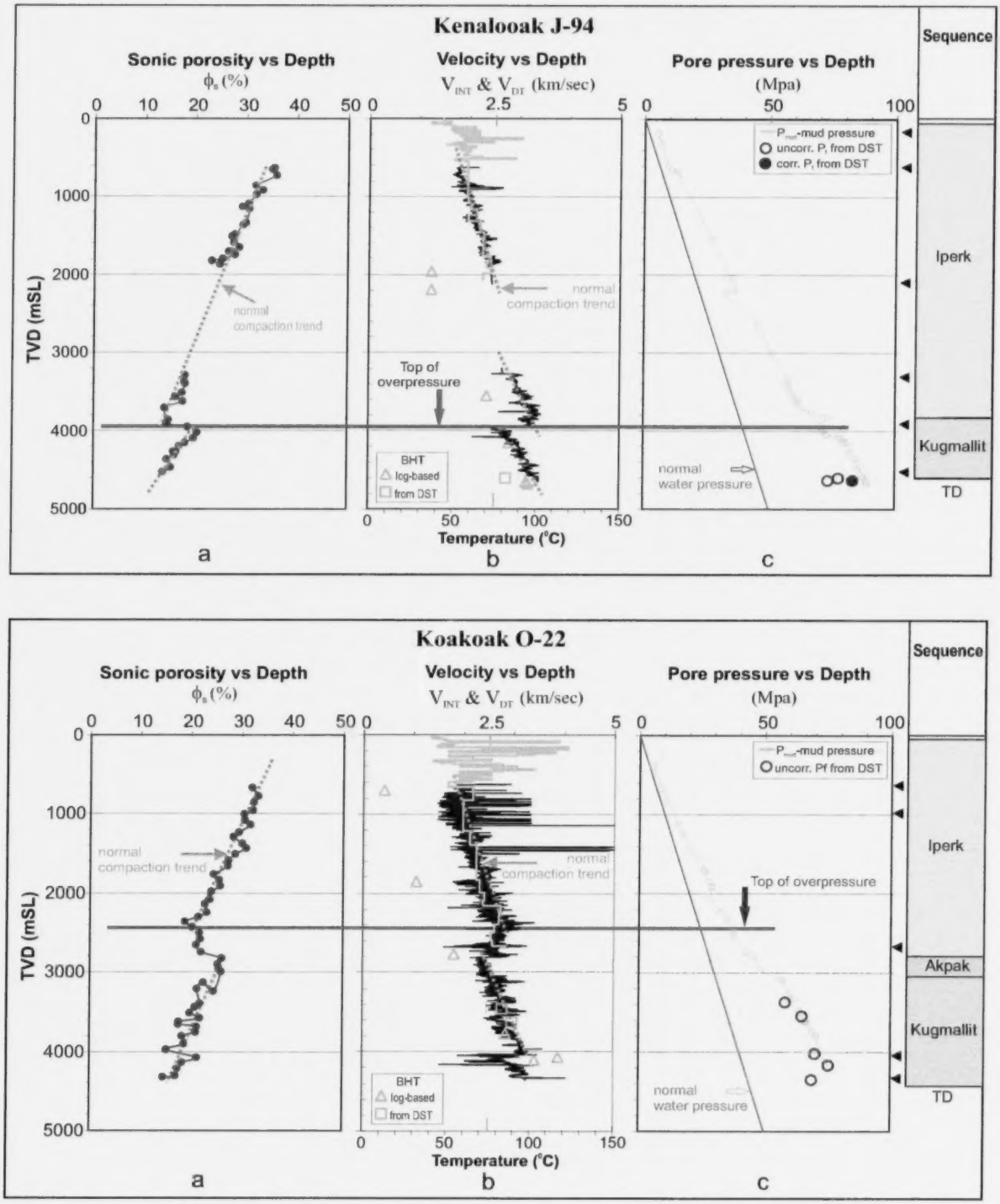
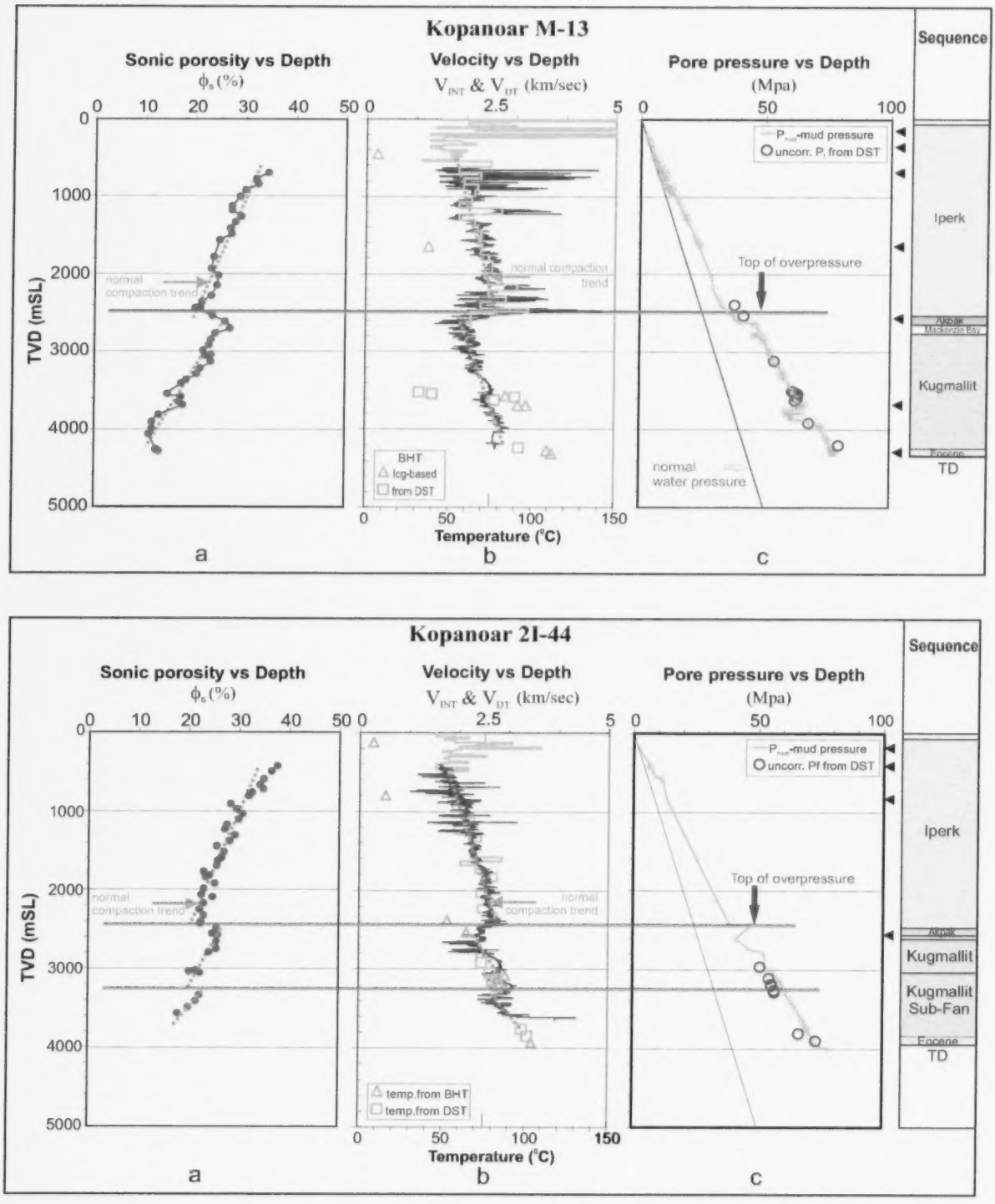


Figure 14a. Overpressure zones delineated in Tertiary strata in the Kenalooak J-94 and Koakoak O-22 wells in the northern Beaufort Mackenzie Basin, based on integrated interpretations of shale sonic porosity (track a), well seismic interval velocity, sonic velocity, and borehole temperature (track b) and pore pressures from well tests and drilling mud weights (track c).



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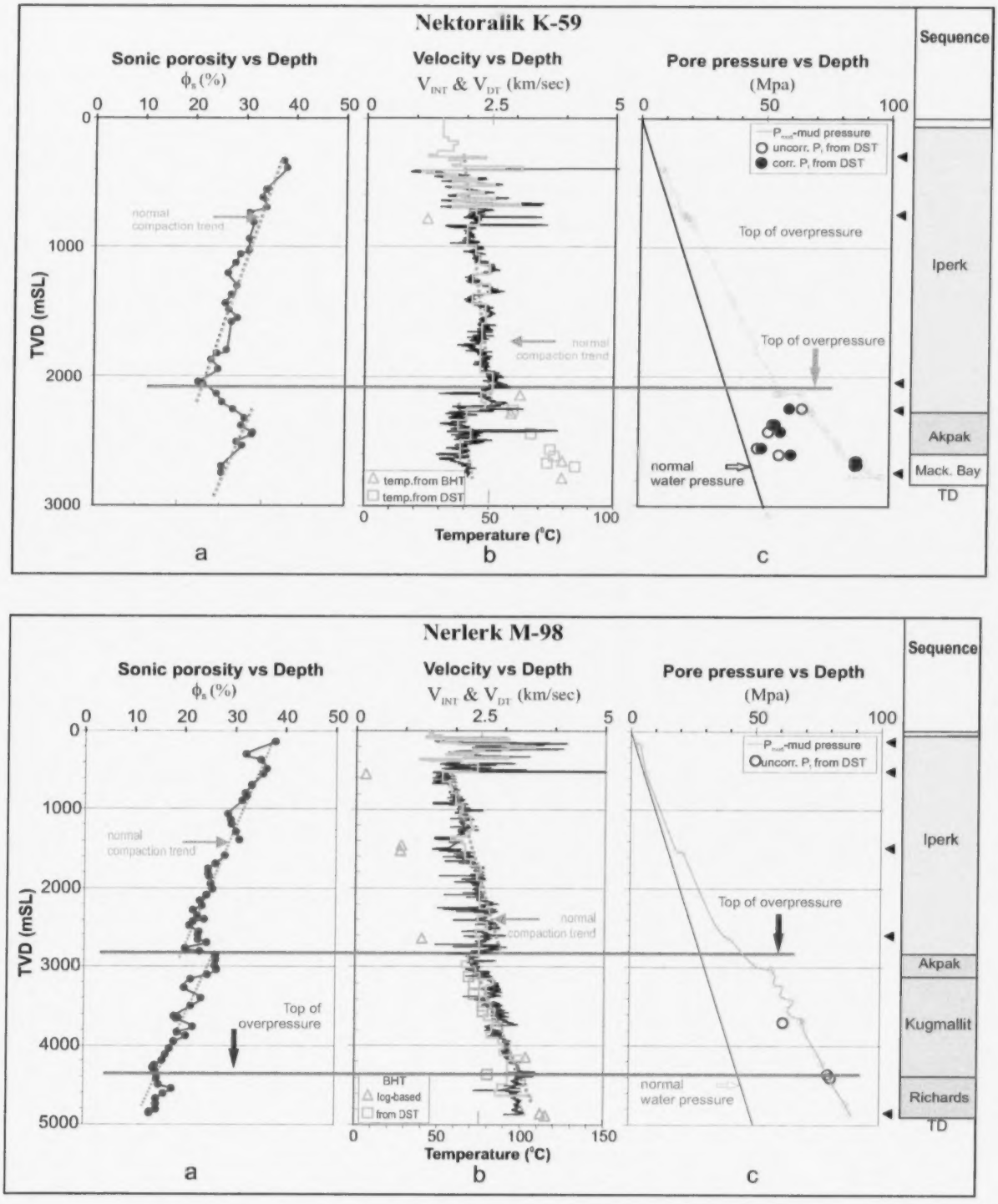

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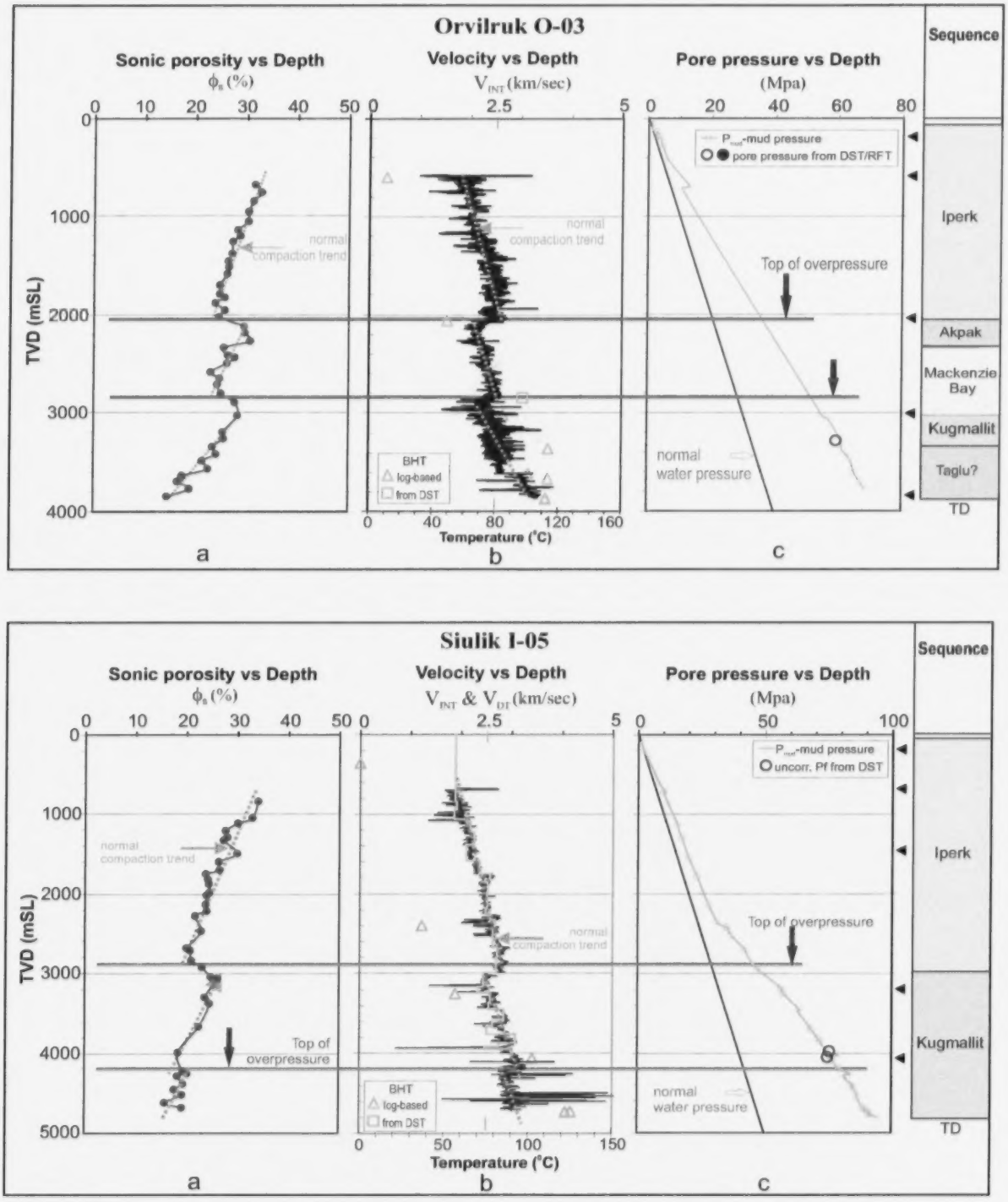
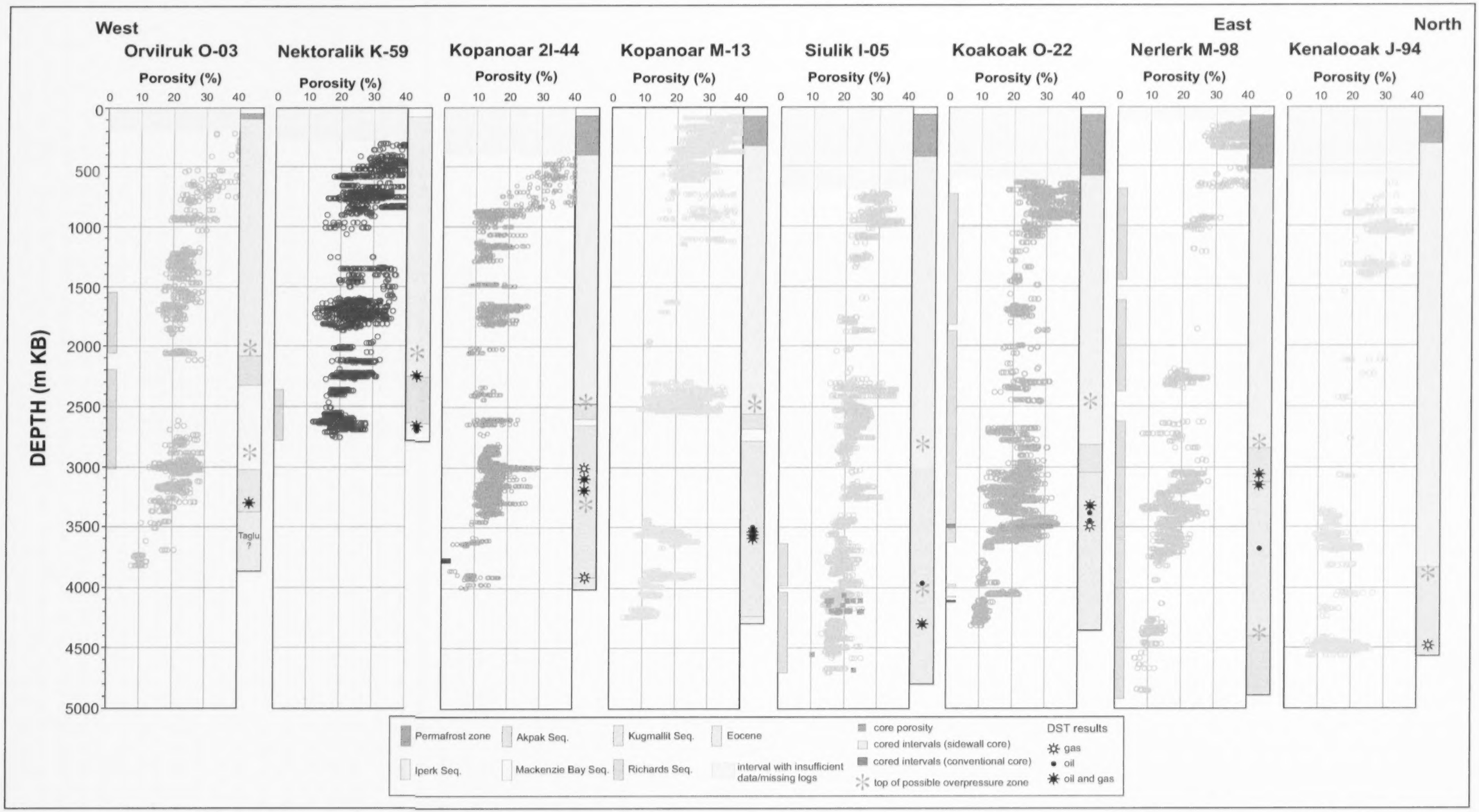


Figure 14d. Overpressure zones delineated in Tertiary strata in the Orvilruk O-03 and Siulik I-05 wells in the northern Beaufort Mackenzie Basin, based on integrated interpretations of shale sonic porosity (track a), well seismic interval velocity, sonic velocity, and borehole temperature (track b) and pore pressures from well tests and drilling mud weights (track c).



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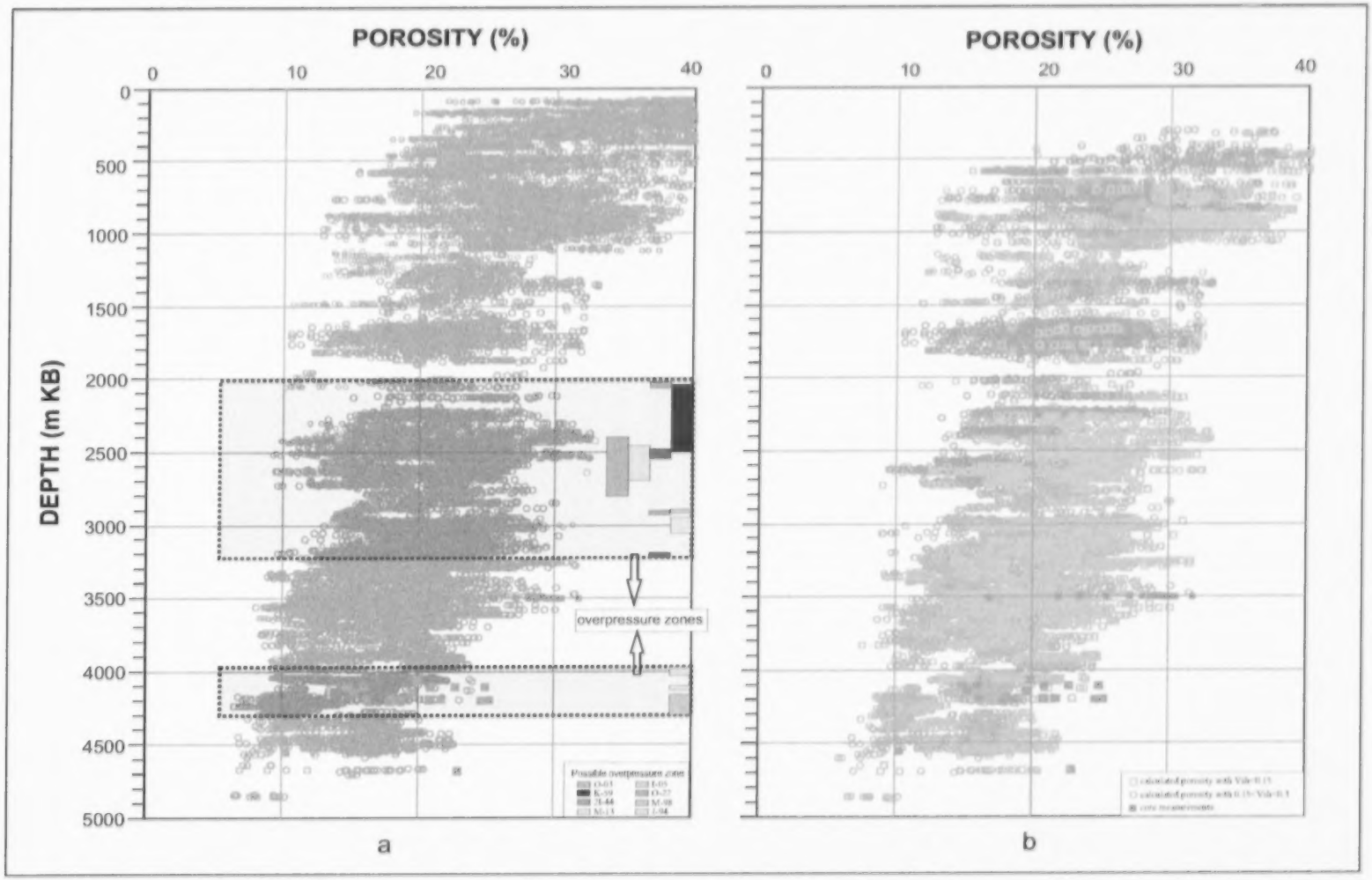

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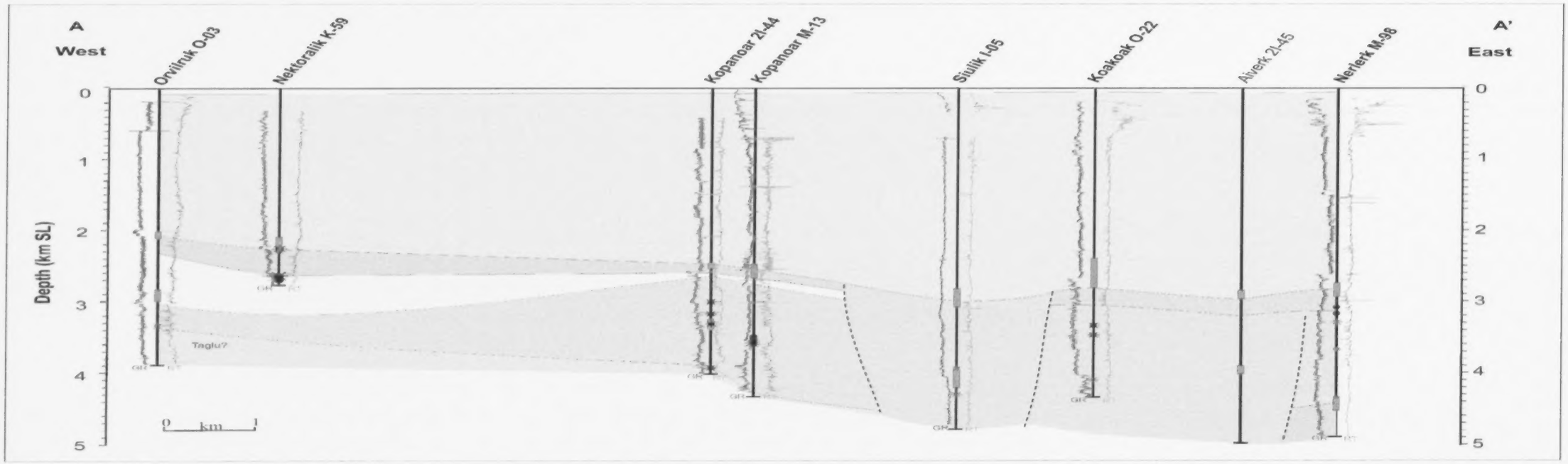

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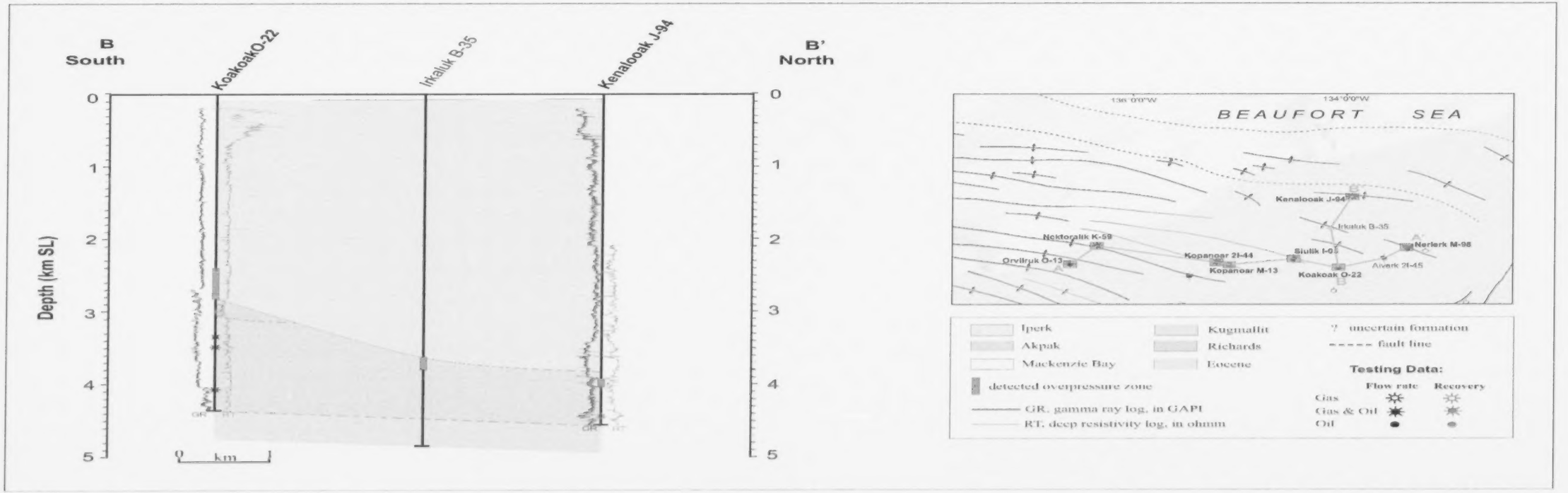

b

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